Experimental study of filament break-off of dense suspensions

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Abstract

Higher particle volume fractions lead to shorter break-off times in filament-stretching measurements, which correlates with higher satellite levels and poorer dot shape when jetted onto a substrate. Suspensions within a certain break-off time range show optimal jetting results. This implies that filament stretching of dense suspensions can be connected to their jetting behaviour, potentially allowing for this technique to be used to predict jetting results. The purpose of this study is to establish a deeper understanding of the break-off process of filaments of dense suspension in order to enable a more repeatable volume deposition of electronic materials, such as conductive adhesives, solder pastes et cetera.

Introduction

The precise and repeatable deposition of functional fluids is increasing in importance in areas such as pharmaceuticals, digital printing, electronics production et cetera. The production of commercial or consumer electronics is dependent on the connection of components and a printed circuit board (PCB) to provide electrical conduction and structural integrity. The rheological characteristics of the functional fluids of interest in these different areas vary radically with respect to viscosity, material loading and viscoelastic properties. Within the realm of electronics production, the material connection between the PCB and the components chosen for the board is provided by an electronic material providing some manner of solder joint. The solder joint is created by depositing a volume of a metallic suspension, called solder paste, on the interconnection areas, or pads, on the PCB, and thereafter placing components on the solder paste. The board, with the solder paste deposits and components, is placed in a reflow oven, which melts the solder paste providing an electrical and structural connection between the PCB and the component. Other electronic materials may be used to provide the electronic and structural integrity of the electronic device, such as conductive adhesives and sintered materials.

As with the jet printing of dyes and other low-viscosity fluids, the jetting of dense fluid suspensions is dependent on the repeatable break-off of the fluid filament into well-formed droplets. It is well known that the break-off of dense suspensions is dependent on the volume fraction of the solid phase, particle size and morphology, fluid phase viscosity et cetera [1-4]. The studies that have been identified in this area are often limited by the imposed shear on the filament through the utilized forcing mechanisms, such as gravity or linear motors. The shear imposed on a filament of fluid during the deposition process is considerably higher than those described in the provided references.

Solder paste consists of an organic resin-based carrier fluid and metal alloy spheres. The metal alloy used in the spheres may vary depending on the specific application, for example SnAgCu for standard electronic applications and SnBi for low-temperature electronic applications. The spherical particles range in size between 2 and 25 µm, see Figure 1. The particle surface is not perfectly smooth but may have small indentations.

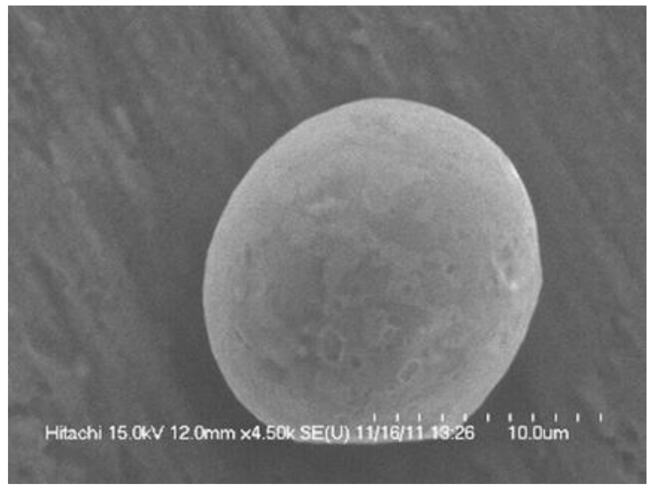

Figure 1 : A scanning electron microscopy image of an individual solder ball of a Sn-Ag-Cu alloy.

The specific size distribution of particles can be varied as well as the volume fraction of particles of the suspension. The fluid is shear-thinning, see Figure 2, the unfilled symbols represent data from rotational rheometry, while the filled symbols represent data from experiments using capillary rheometry. The viscosity decreases by three orders of magnitude for an increase of shear rate by four orders of magnitude.

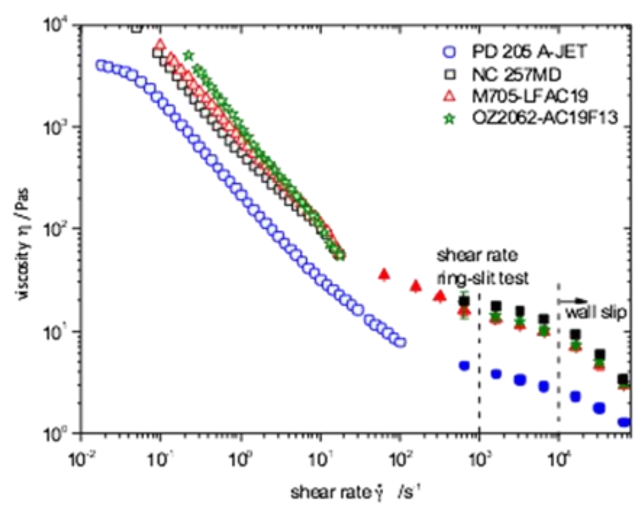

Figure 2 : Viscosity as a function of shear rate for three solder paste samples (□ , ▵ and ☆) together with an adhesive sample (○).

The goal of this study is to study the dynamics of filament break-off for dense suspensions with various particle size distributions and particle volume fractions. Further, the filament break-off characteristic will be correlated with quantitative measures of jetting quality.

Experimental methods

The suspension samples consist of a resin-based flux and tin/copper/silver spherical particles with diameters of 2–25 µm and metal loadings of 83–87 wt%. The size distribution of the particles is approximately Gaussian with a diameter deviation of $\sigma_{dp} = 0.20 \cdot d_p$.

The experimental setup consists of a Filament Break-Off (FILBO) device developed in-house. A cylindrical sample (diameter = 1 mm and height = 1 mm) of the suspension is extended using a cylindrical probe travelling between 100–800 mm/s in the vertical direction (Fig. 3). The filament minimum diameter is followed over time during filament extension with an imaging frequency of 8600 frames/sec. Imaging was performed with a Phantom Miro 310 (Vision Research, New Jersey, USA) high-speed camera.

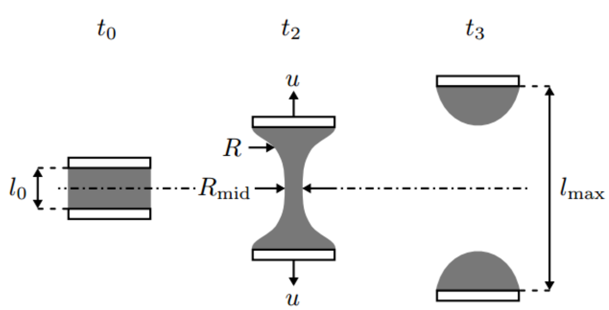

Figure 3 : Principle of extensional rheometry where a fluid element is placed between two plates at an initial distance, lo. The plates move in opposite directions until a maximum distance lmax with a constant velocity u. A ligament establishes with a certain radius R and thins until break–up, where the mid–filament radius R_{mid} is observed.

Imaging data was also obtained for the jetting of the chosen suspensions. Jetting of the fluids was performed with a piezo-driven jet printer (Mycronic AB, Sweden), see Figure 5. To create droplets with stable flight of this highly viscous medium at the desired droplet volumes requires an adequately high exit velocity. A design comprising a piston moved by a piezoelectric actuator and a return spring was selected. To a first approximation, piston movement is linear in applied actuator voltage. The actuator, however, represents both electrical and mechanical inertia in that it has a large capacitance and a finite resonance frequency. Since the piezoelectric material will generate an electric field when subjected to mechanical stress some care must be taken when interpreting voltage measurements, such as the ones shown in Figure 4.

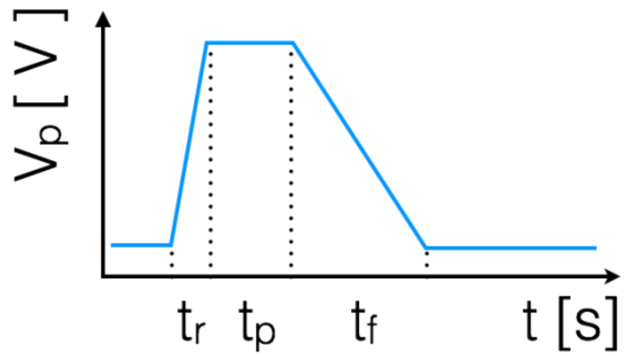

Figure 4 : Schematic of the electrical actuation profile used during the ejection process.

The movement of the piezo will induce movement of a piston which in turn will produce a displacement of the fluid in the jetting chamber, see Figure X. The above-mentioned conversion of kinetic energy of the piston to the kinetic energy of the fluid will be tempered by the hydrodynamic resistance that the fluid meets as it moves through the nozzle.

Jetting experiments were performed by syncing the ejector pulse with the camera trigger and recording images during droplet ejection and breakup into free space. Images were recorded at 116 000 frames per second.

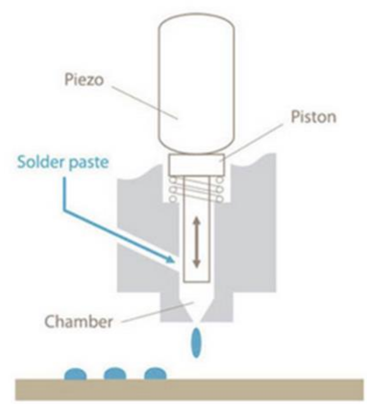

Figure 5 : Schematic of the jetting principle that is the impetus of this study.

To evaluate the quality of the deposit of fluid on the substrate, a number of measures are extracted, these being positioning in x and y, diameter, height, deposit shape, satellite production and volume, see Figure. To obtain the position of the deposit, the center of mass of a thresholded grey scale image of the deposit from above is calculated. Using the area of the thresholded image, the diameter of an equivalent circular area can be calculated. The same image also provides information about satellites, which are separate bodies of fluid outside the main volume of fluid. The height and volume of the deposit are obtained using the solder paste inspection apparatus. To estimate the roundness of the dots a root mean square deviation of the distance from each pixel on the dot boundary minus the average radius of the dot was calculated.

For a perfect circle this measure would be zero; however the finite pixel size means that we will always see a small positive value.

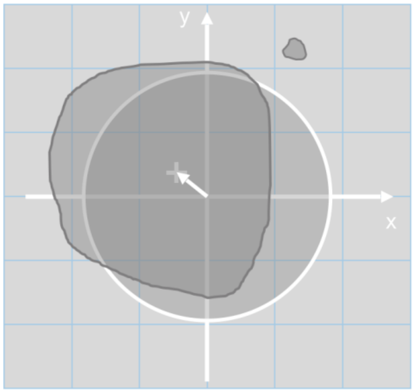

Figure 6 : Idealized sketch of an ideal and an actual deposit.

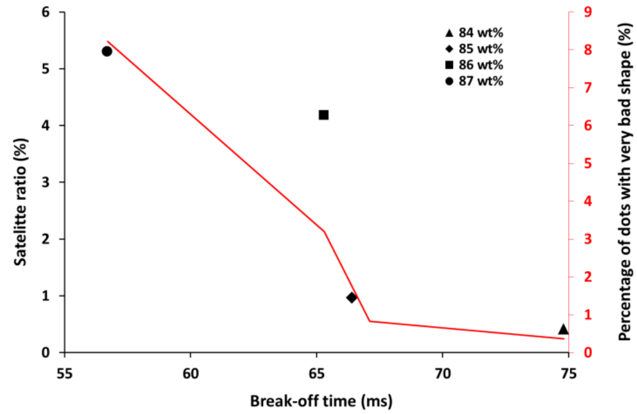

Figure 8 : Satellite ratio and percentage of dots with very bad shape when jetted onto substrate plotted against break-off time from FILBO measurement for solder pastes with 84 (▲), 85 (♦), 86 (■) and 87 (●) wt%.

Results and Discussion

High speed imaging of the filament breakup process showing the effect of metal loading is presented in Figure 7. Filaments that were formed with higher metal loadings broke significantly earlier than those with lower metal loadings and the trend is consistent for all the volume fractions tested in this study.

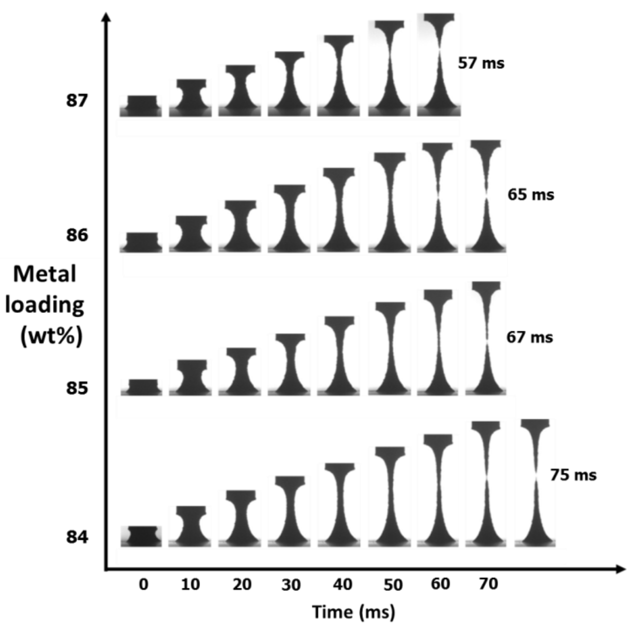

Figure 7: Sequences of images showing the filament breakup of solder paste suspensions with 84, 85, 86 and 87 wt%.

When jetted onto a substrate, pastes with higher metal loading also result in higher satellite levels and a higher number of dots with very bad shape, see Figure 8.

Imaging of jetting dynamics of solder pastes also showed an accelerated thinning and pinch-off for suspensions with increasing metal loading (the **x** symbol notes the complete pinch-off of the filament head in each sequence), as seen in Figure 9.

Conclusions

The Filament Break-Off (FilBO) device provides an effective setup for performing extensional filament breakup experiments on dense and viscous fluids. The device allows for the flexible variation of extensional shear on the break-off of a filament.

It has been found that higher metal loadings in solder paste suspensions result in a process of accelerated thinning and pinch-off of the filament both under extensional filament stretching and during jetting. This accelerated break-off speed could explain the higher satellite level and poorer dot shape when these pastes are jetted onto substrates. This seems to suggest that the utilization of solder pastes, or other electronic materials, that have a smaller diameter of the solder spheres will increase the repeatability of volume deposition and the quality of the resulting deposited volumes.

Extensional filament stretching can therefore be used as a technique to characterize dense suspensions and relate these properties to high-speed jetting applications.

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Author Biography

Gustaf Mårtensson received his MS in engineering physics from the Royal Institute of Technology (KTH) in Stockholm, Sweden (2000), and his PhD in fluid mechanics also from the Royal Institute of Technology (KTH) (2006). After receiving his PhD, Gustaf began working at Mydata Automation AB in the area of jetting of complex fluids. He continued his research in this area at Chalmers University of Technology (CTH) in the areas of complex fluids and nanomaterials. Gustaf continues his work as an Expert of Complex Fluids at Mycronic AB and an adjunct researcher at the Royal Institute of Technology (KTH).

Fabian Carson obtained his MS in Chemistry at University College London (UCL) (2009) After research work at University St. Andrews in Scotland and UC Berkley in the United States of America, Fabian obtained his PhD in chemistry at Stockholm University in Stockholm, Sweden (2015). Fabian works in the area of jetting of functional fluids at Mycronic

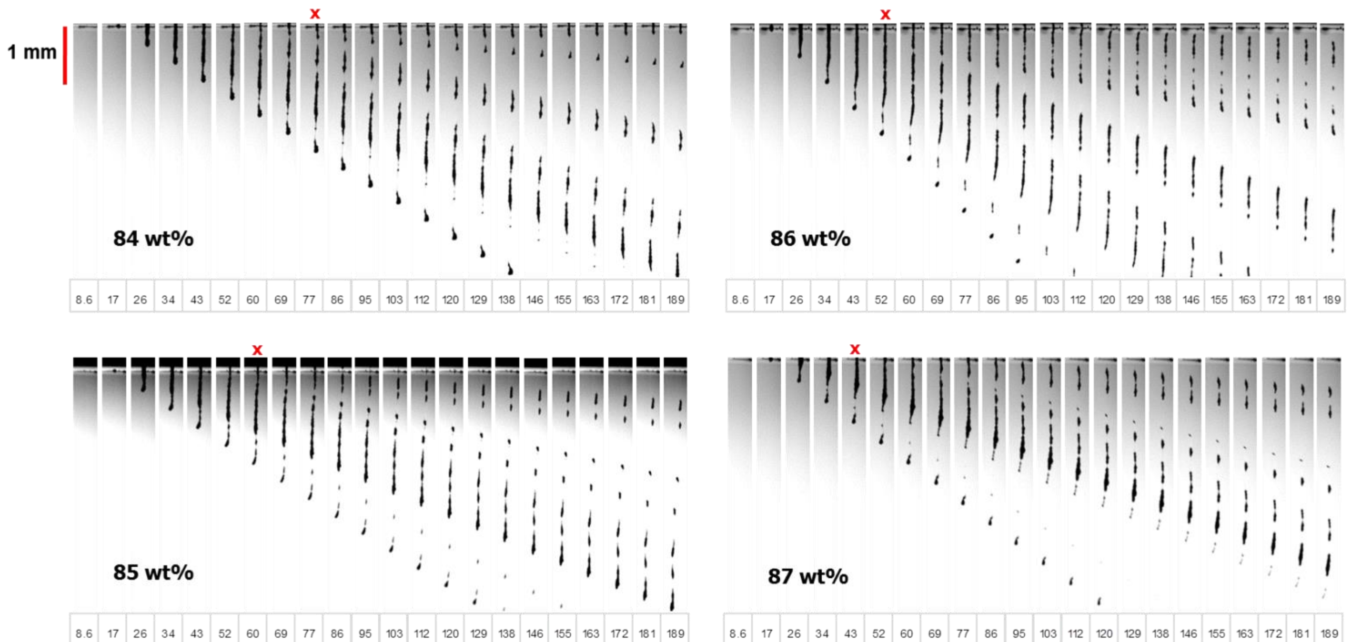

Figure 9 : Sequences of images showing the jetting of solder paste with 84–87 wt% using the same input ejection energy. Numbers below each image indicates time after droplet ejection in µs. The scale bar corresponds to 1 mm. The x symbol indicates complete pinch-off at the filament head.